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Mesoclimatic studies in the Upper Don Basin, Aberdeenshire

By R. J. A. Jones*, J. Tinsley and M. N. Court

(Soil Science Department, University of Aberdeen)

Summary

Measurements of solar radiation, air and soil temperature, rainfall and exposure to wind from 14 stations, 270–700 m O.D., in the Upper Don Basin, Aberdeenshire, were recorded for 1966–70. From mid-July to late September solar radiation totals were slightly greater in this upland area than near the coast at Aberdeen and greater at 670 m O.D. than at 351 m O.D. A sucrose inversion method, giving exponential mean temperatures, θ_e values, was used for measurements in air and soil at all sites and comparisons were made with data collected from a limited number of calibrated thermographs and mercury thermometers. Monthly mean θ_e values averaged 2 °C higher than arithmetic means (θ values). The overall annual mean air temperature recorded by standard instruments was 6 °C. Lapse rates per 100 m rise of 0·64 °C for air temperatures and 0·61 °C for soil temperatures were established from θ_e values. Variations in the periods of the growing season when mean air temperatures remained above 6 °C (GL) and above 10 °C (HGL) were estimated from the temperature curves constructed from 5 day means measured by thermograph, and from θ_e values. Whereas GL decreased by 10 days for every 200 m rise, HGL fell by 10 days for each 50 m rise in altitude. The normal annual rainfall total of about 1000 mm for 1964–70 is compared with totals for other stations in north-east Scotland. A small potential soil moisture deficit of about 50 mm developed in 2 years out of 6 at one station below 400 m O.D. in the Upper Don Basin. The relative exposures of sites were assessed using the tatter flag method and data compared with anemometer readings. Strong correlations were found confirming that tatter flags are useful substitutes for or complements to anemometers for studies in exposed areas. The implications of changes in mesoclimate in this upland area of north-east Scotland are assessed and the value of the non-standard techniques tested is established.

1. Introduction

Detailed observations on the climate of inland areas in north-east Scotland are available from the long-term meteorological stations of Braemar (National Grid Reference NO 152914) and Balmoral (NO 260947) and for other meteorological stations including Dinnet (NJ 446025) and Glenlivet (NJ 188303). Records from Craibstone (NJ 872107) provide a comparison with coastal areas. These characterize the Grampian regional climate as one of rather cold winters and fairly cool summers with moderate rainfall evenly distributed throughout the year. On their climatic maps of Scotland,

* Present address: Soil Survey of England and Wales, c/o Ministry of Agriculture, Fisheries and Food, Woodthorne, Wolverhampton, West Midlands WV6 8TQ.

Birse and Dry (1970) and Birse and Robertson (1970) delineate the lower parts of the Upper Don Basin as fairly warm, moist, moderately exposed lowland and foothill, and the higher parts as cool wet foothill and upland which is exposed to very exposed with moderate to severe winters.

The data from established meteorological stations give little insight into variations of mesoclimate. To some extent these can be inferred from established relationships between climatic and physiographic variables (Gloyne 1968; Manley 1945; Smith 1950) but where the density of recording stations is low such interpolation can often be misleading.

As part of an experimental program to determine the factors affecting the productivity of mixed grass swards containing clover in the Upper Don Basin, Aberdeenshire, a net of 14 meteorological stations (Figure 1) was operated for 1966–70 by the Soil Science Department, University of Aberdeen. Solar radiation, air and soil temperature, rainfall and exposure to wind were recorded using standard and non-standard instruments (Table I). This paper describes the methods employed and examines the variations of climate with changing altitude and aspect. Although the emphasis is on the effects of changing topography, the results are also placed into a regional context.

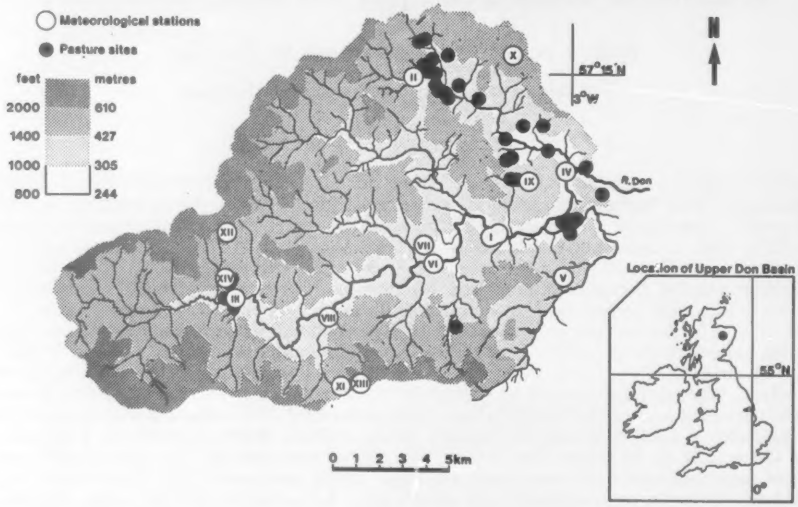

Figure 1. Meteorological stations in the Upper Don Basin.

2. Experimental

(a) *Solar radiation*

Differential interception of solar radiation in hill areas by differently oriented slopes greatly influences air and soil temperatures in northern Britain (Gloyne 1968). Despite its fundamental significance, few attempts have been made to measure solar radiation in the hill lands of the United Kingdom (Hughes and Munro 1968).

Measurements were therefore made at Stations VIII (351 m O.D.) and XII (670 m O.D.) from June to December 1969. At the lower site a Lintronic solarimeter (manufactured by Lintronic Ltd, London, in co-operation with Rothamsted Experimental Station) was connected to an integrating millivolt counter with a six digit recorder and mounted in a wooden box, the top of which provided a base

Table I. *Details of meteorological stations in Upper Don Basin*

No.	Station	Alt. (m O.D.)	NGR (NJ)	Period of operation	Sucrose tube*	Tatter flag	Max./ Min.†	Thermo- graph	Rain- gauge†	Anemo- meter	Solari- meter
I	Waterside	275	366119	30/04/66–30/04/70	×	×		×		×	
II	Glenbuchat Lodge	381	332189	30/04/66–30/04/70	×		×		×		
III	Allargue Hotel	411	256092	30/11/68–30/04/70	×			×			
IV	Mains of Glenbuchat	275	397147	30/04/67–30/04/70	×		×		×		
V	South Ardgeith	381	397102	31/05/66–30/04/70	×	×	×		×		
VI	South Candacraig	305	340107	31/05/66–31/10/68	×	×	×				
VII	North Candacraig	404	337116	31/05/66–30/04/70	×	×	×		×	×	
VIII	Tornahaish	351	296084	30/04/66–30/04/70	×		×		×		×
IX	Ben Newe	565	381142	31/05/66–30/04/70	×	×	×		×	×	
X	Creag an Sgor	600	375197	31/05/66–30/04/67	×	×	×		×		
XI	Glas Choille	549	301054	31/05/66–30/11/68	×	×	×		×		
XII	Lecht	670	252121	30/11/68–30/04/70	×	×	×		×	×	×
XIII	Scraulac	686	309055	31/05/66–30/04/70	×	×	×	×	×		
XIV	Allargue Hill	550	253100	30/09/68–30/04/70	×	×			×		

* for mean air and soil temperature measurements.
† daily readings at Station II, all other thermometers and rain-gauges read monthly.

for the solarimeter dome 1·6 m above ground level. A Kipp and Zonen solarimeter (as part of a Plessey automatic climatological recording station) with its dome mounted approximately 5 m above the ground was used at the higher site. A standard Kipp solarimeter mounted on the roof of the Natural Philosophy Building (30 m O.D.), University of Aberdeen, was used to calibrate these instruments and provide data from near sea level for comparison.

(b) *Temperature*

To relate air and soil temperatures to sward growth, the sucrose inversion method for measuring exponential mean air and soil temperatures was developed (Jones 1972; Jones and Court 1980). It was used at 46 sites throughout the Upper Don Basin between May 1966 and April 1970.

Two sealed polythene tubes containing a sucrose buffer solution were positioned at each experimental site and changed at monthly intervals as described by Jones and Court (1980). One tube was clipped in a north-facing recess $7{\cdot}5 \times 4 \times 4$ cm deep in a post also carrying a tatter flag (Plate I) such that the centre of the solution was 1 m above the ground. The second tube was placed in a stoppered copper tube 10 cm $\times$ 2 cm internal diameter inserted vertically into a hole in the ground beside the post such that the centre of the solution was at a depth of 10 cm below the surface.

At those sites where herbage yields were measured the sucrose tubes provided estimates of monthly mean temperatures throughout the growing seasons 1966–69. At the meteorological stations the tubes were mounted alongside standard thermograph and mercury thermometers for calibration purposes (Table I).

A Cambridge mercury-in-steel thermograph measured air and soil temperatures continuously at Station I (275 m O.D.) for the period April 1966 to April 1970. All the readings were reduced by planimeter to monthly means to permit comparison with data from other instruments. A Casella thermograph of the bimetallic type was installed in a Stevenson screen at Station III (411 m O.D.) and the period of recording was November 1968 to April 1970. Daily readings were obtained from a mercury thermometer at Station II (381 m O.D.) from April 1966 to April 1970. The temperature sensor in all these instruments was positioned 1 m above the ground and field calibrations against NPL mercury thermometers reading to $\pm 0{\cdot}1$ °C were undertaken.

(c) *Precipitation*

Rainfall is difficult to measure in rugged country where rain-gauging may suffer local bias depending on the relative directions of slope and the direction and speed of wind.

Rainfall and snowfall were measured daily at Station II (381 m O.D.) for 1964–70 using a standard meteorological copper rain-gauge with a 12·5 cm diameter funnel, the brass lip of which was 0·3 m

above the ground, as part of the Meteorological Office program to collect precipitation data in the United Kingdom. Rainfall was also measured, at ten other stations in the Upper Don Basin, totals being recorded only at monthly intervals. Monthly totals were obtained from meteorological stations in areas adjacent to Donside for comparison.

(d) *Wind exposure*

To assess exposure at ten of the meteorological stations and at the sward sites, measurements of flag tatter and geomorphic shelter were made. Conventional 3-cup-type anemometers were also employed at four of the meteorological stations to provide data for comparison with the non-standard techniques.

(1) *Tatter-flag technique.* This cheap and convenient index of exposure involved the tattering of standard cotton flags. Their use is described elsewhere by Thomas (1959), Rutter (1968) and Gloyne, MacSween and Allen (1975). In the present study the method of Lines and Howell (1963) was used. The flags were made of Madapollam cloth (DTD 343A), 30 × 41 cm, each being dried at 60 °C, cooled in a desiccator and weighed to $\pm 0{\cdot}005$ g before being sewn on to galvanized steel rods 61 cm long and 6 mm diameter. One flag post and holder was placed at each experimental site such that the top of the flag when mounted was 1·5 m above the ground (Plate I).

After exposure for 2 months or at very exposed stations (IX, XII and XIII) after 1 month, during which the corners and free edges tattered away, each flag was replaced by a new one, the tattered flag being carefully washed, dried at 60 °C, cooled and reweighed. The loss in weight was then converted to $cm^2\ d^{-1}$ for the period of exposure.

Duplicate flags placed either side of the river Don (30 m apart) at Station I showed a mean coefficient of variation of 12 per cent over a period of two years (Jones 1971).

(2) *Geomorphic shelter.* The method used was that first suggested by Blust and de Cooke (1960), in which the geomorphic shelter at a particular site is found by measuring the angle between the horizontal and the skyline for each of the 16 principal compass bearings. The angles recorded in this way are then summed to give the exposure index of the site. If the index is high the site is sheltered and if low it is exposed. Three indices were determined for sites in the Upper Don Basin; the first described above, the second by summing only the 8 principal compass bearings of N, NE, E, SE, S, SW, W and NW, and the third by using the 16-point data and doubling the values for the SSW, SW, WSW, W, WNW and NW directions before summation, to weight the index with respect to the predominant wind direction.

(3) *Anemometers.* Three instruments were installed on level sites 1·5 m above the ground surface at Stations I (275 m O.D.), VII (404 m O.D.) and IX (565 m O.D.) alongside tatter flags (Table I). A fourth anemometer was located at Station XII as part of the Plessey automatic weather station.

3. Results

Full details of the data were recorded by Jones (1971).

(a) *Solar radiation*

Figure 2 presents the monthly means at Aberdeen for the years 1967–69, with data for the summer months in 1969 at Station XII (670 m O.D.). Daily mean totals at Stations VIII (351 m O.D.) and XII compared with those for Aberdeen for the period June to September 1969 are displayed in Figure 3. The values for Aberdeen are monthly means of consecutive daily totals whilst observations from Stations VIII and XII, especially in August and September, were interrupted by instrument failures. The monthly means from continuous observations in Aberdeen, however, compare favourably with means computed from the totals on only those days during which measurements were made in Upper Donside (Figure 2).

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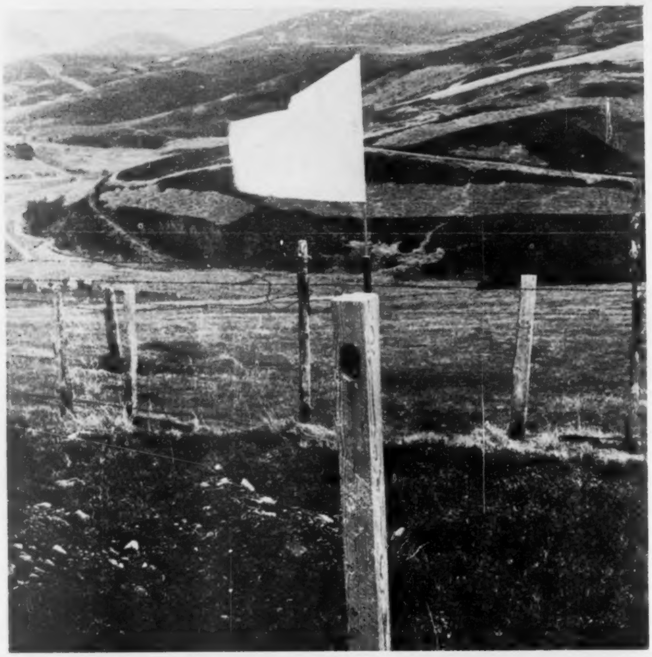
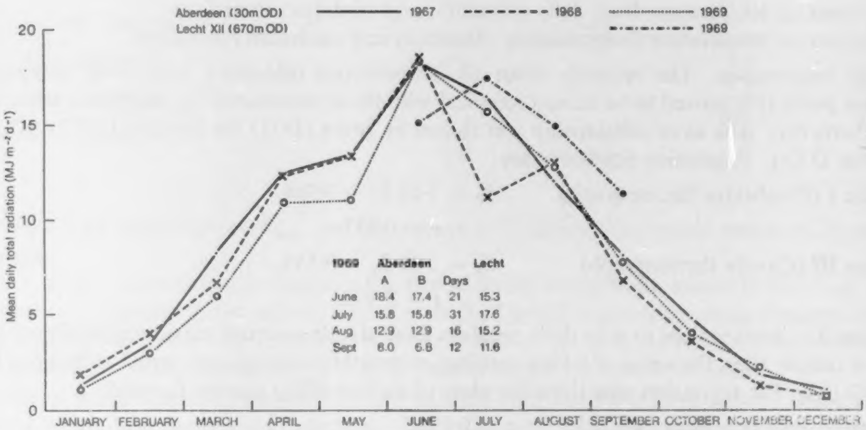


Plate I. A tatter flag for measuring wind exposure and a tube containing sucrose solution for mean air temperature measurement at Upper Badenyon, Glenbuchat, Upper Don Basin, Aberdeenshire.

The monthly peak at Aberdeen occurred in June each year of 1967–69 at slightly above 18 MJ m^{-2} d^{-1}. The Upper Donside figures show a contrast with a peak at Station XII in July 1969 at slightly below 18 MJ m^{-2} d^{-1} (Figure 2). Daily totals show that, although lower in June, solar radiation continued to be higher in the Upper Don Basin than at Aberdeen throughout August and September, a trend which is clear in Figure 3.



The values for Aberdeen are derived (A) from continuous recordings and (B) from those days in each month when solar radiation was recorded at Station XII

Figure 2. Solar radiation, as monthly means of daily totals (MJ m^{-2} d^{-1}), at Aberdeen and the Lecht.

Figure 3. Solar radiation at two stations in the Upper Don Basin compared with Aberdeen in 1969.

(b) *Temperature*

The following *monthly* mean temperatures were measured by the sucrose inversion method, thermograph and maximum and minimum thermometers:

$\theta_{e(a)}$ exponential mean air temperature by sucrose inversion
$\theta_{e(s)}$ exponential mean soil temperature by sucrose inversion
θ_a mean air temperature from thermograph charts by planimeter
θ_s mean soil temperature from thermograph charts by planimeter
θ_d mean air temperature from daily maximum and minimum recordings
θ_m mean air temperature from monthly maximum and minimum recordings.

(1) *Air temperature.* The monthly mean air temperatures calculated from daily maximum and minimum peaks (θ_d) proved to be almost identical with those determined by planimeter from thermograph charts (θ_a). The close relationship was shown by Jones (1971) for Stations I (275 m O.D.) and III (411 m O.D.). Regression equations are:

Station I (Cambridge thermograph) $\theta_d = 1{\cdot}01\,\theta_a + 0{\cdot}366$, $r = 0{\cdot}997$;

Station III (Casella thermograph) $\theta_d = 1{\cdot}03\,\theta_a - 0{\cdot}545$, $r = 0{\cdot}992$.

Because it is inconvenient to take daily readings from simple mercury maximum/minimum thermometers at remote sites, the value of taking readings at monthly intervals was tested at Stations I and II (381 m O.D.). The regression equations for plots of θ_m (monthly) against θ_d were:

Station I $\theta_m = 1{\cdot}14\,\theta_d - 0{\cdot}745$, $r = 0{\cdot}972$;

Station II $\theta_m = 1{\cdot}09\,\theta_d - 0{\cdot}737$, $r = 0{\cdot}976$.

Clearly the mean of the monthly maximum/minimum values is of use for general comparisons but less precise for scientific purposes.

These data were also used to examine the relationships of arithmetic mean to exponential mean (θ_e) temperatures (Figure 4) and regression equations are given in Table II. It is clear that exponential

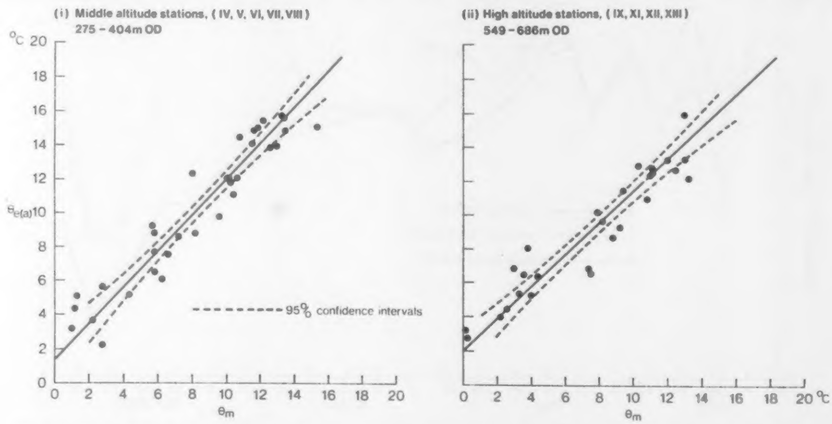


Figure 4. Relationship between $\theta_{e(a)}$ and θ_m values for several sites in the Upper Don Basin.
(i) $\theta_{e(a)} = 0.956\,\theta_m + 2.183$, $r = 0.952$; (ii) $\theta_{e(a)} = 0.830\theta_m + 2.731$, $r = 0.942$.

Table II. *Relationship between air and soil temperatures at Station I, 275 metres O.D.*

		Percentage variance	Thermograph θ_s	Thermograph θ_a	Sucrose inversion $\theta_{e(s)}$	Sucrose inversion $\theta_{e(a)}$
			degrees Celsius			
(i) θ_s	$= -0{\cdot}25 + 0{\cdot}816\theta_a$	91	4·6	6·0		
			7·9	10·0		
(ii) $\theta_{e(s)}$	$= -0{\cdot}90 + 0{\cdot}960\theta_{e(a)}$	94			7·2	8·4
					11·0	12·4
(iii) $\theta_{e(s)}$	$= 0{\cdot}96 + 1{\cdot}285\theta_s$	90	4·6		6·9	
			7·9		11·1	
(iv) $\theta_{e(a)}$	$= 2{\cdot}49 + 0{\cdot}989\theta_a$	93		6·0		8·4
				10·0		12·4
	by equation (iii)		4·5		6·7	
			8·0		11·2	
	by equation (ii)				6·8	8·0
					10·6	12·0
Rounded mean temperatures			4·5	6·0	7·0	8·0
			8·0	10·0	11·0	12·0

mean monthly air temperatures, $\theta_{e(a)}$, are on average 2 °C higher than means measured by standard instruments.

It is not strictly appropriate to compare the two different temperature means in this way, because of the inherent properties of the sucrose inversion method which biases the average obtained in favour of higher relative to lower temperatures. It is expedient to do so here, however, because only the sucrose method was used at some meteorological stations and all the pasture sites.

A profile of air temperatures θ_a, θ_d in the Upper Don Basin for 1966–70 (Figure 5) shows that they are low in winter and moderate in summer. Table III gives monthly mean air temperatures for a number of stations in north-east Scotland for comparison. Temperatures in the Upper Don Basin are similar to those at Balmoral and Braemar, with altitudes similar to Waterside (I) and Glenbuchat Lodge (II) respectively. By contrast, temperatures are higher throughout the year at Craibstone near Aberdeen and at Dinnet.

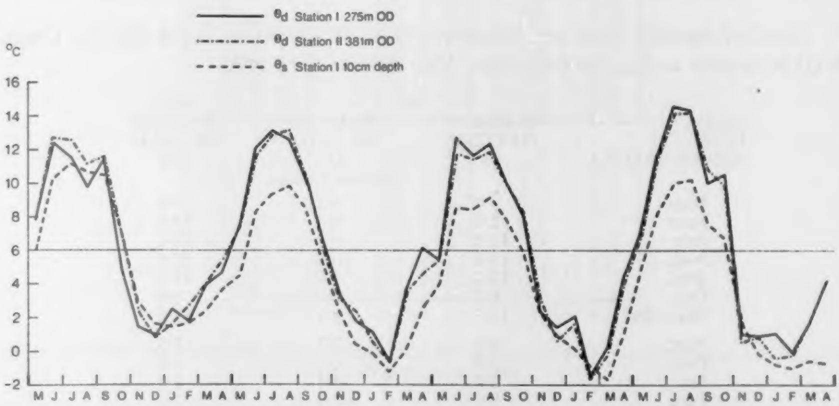


Figure 5. Monthly mean air and soil temperatures by thermograph and mercury thermometer in the Upper Don Basin, 1966–70.

Table III. *Standard monthly mean air temperatures for stations in the Upper Don Basin in relation to data from other meteorological stations in Aberdeenshire*, May 1966 to April 1970*

Station	Waterside	Glenbuchat Lodge	Braemar	Craibstone	Dinnet	Glenlivet	Balmoral
NGR	NJ 366119	NJ 332189	NO 152914	NJ 872107	NJ 446025	NJ 188303	NO 260947
Altitude (m O.D.)	275	381	339	91	177	215	283
				degrees Celsius			
May	6·6	6·8	7·0	7·8	7·9	7·7	6·6
June	11·8	11·9	12·1	12·2	13·0	12·5	11·5
July	12·2	12·8	12·8	13·4	13·6	(13·7)	12·5
Aug.	11·8	12·6	12·4	13·0	13·3	(13·0)	12·0
Sept.	9·9	10·8	10·9	12·0	11·9	11·4	10·4
Oct.	7·3	7·8	7·7	9·4	8·9	8·8	7·7
May–Oct.	9·9	10·4	10·5	11·3	11·5	11·2	10·2
Nov.	1·7	2·3	2·1	4·2	3·4	3·1	1·9
Dec.	1·2	1·2	1·6	3·3	2·5	2·3	1·3
Jan.	1·4	0·9	1·5	3·2	2·4	2·4	1·3
Feb.	−0·4	0·1	−0·7	1·8	0·5	0·6	−0·7
Mar.	1·8	2·2	1·9	4·0	3·3	3·1	2·0
Apr.	4·2	4·5	4·3	5·8	5·7	5·3	4·3
May–Apr.	5·8	6·2	6·1	7·5	7·2	7·0	5·9

* Glenlivet is in Banffshire.
Figures in brackets are estimates because of incomplete data.

(2) *Soil temperature.* Few long-term records of soil temperature exist for stations in north-east Scotland and those for Craibstone (91 m O.D.), near Aberdeen, measured at 10 cm depth, are reproduced in Table IV for comparison with measurements from Waterside (I, 275 m O.D.). Soil temperatures, θ_s, in the Upper Don Basin during May 1966–April 1970 are lower than those near the coast though the difference is larger than might have been expected. The only explanation is that moderating maritime influences are strong at Craibstone and the frost pocket at Waterside (I) keeps soil temperatures low, particularly during winter.

The corresponding data measured by sucrose inversion, $\theta_{e(s)}$, are also given. As Jones and Court (1979) point out, θ_s values are 2·0–2·5 °C lower than $\theta_{e(s)}$ values, on a monthly mean basis. From the profiles of air and soil temperatures during the 1969 growing season it is clear that, in the altitude range 330–550 m O.D., mean soil temperatures lag below air temperatures until July/August (Figure 6).

Table IV. *Standard monthly mean soil temperatures at 10 centimetre depth* (θ_s) *for Craibstone and Waterside* (I) *in relation to* $\theta_{e(s)}$ *for Waterside, May 1966 to April 1970*

	θ_s		$\theta_{e(s)}$
Station	Craibstone	Waterside	Waterside
NGR	NJ 872107	NJ 366119	NJ 366119
Altitude (m O.D.)	91	275	275
		degrees Celsius	
May	8·4	4·8	7·4
June	12·9	8·8	12·4
July	14·2	9·8	14·7
Aug.	13·8	10·0	12·8
Sept.	12·2	8·6	12·3
Oct.	8·7	6·5	9·4
May–Oct.	11·7	8·1	11·5
Nov.	4·4	2·3	3·6
Dec.	2·9	0·7	3·4
Jan.	2·8	0·4	2·6
Feb.	1·9	−0·4	2·6
Mar.	3·0	0·1	2·8
Apr.	5·4	1·6	4·2
May–Apr.	7·5	4·4	7·4

(3) *The effect of altitude on temperature.* The use of the sucrose inversion method for mean temperature measurement permitted the collection of data from a large number of sites at different altitudes. Such data are lacking, particularly for soil temperature in upland areas (Harrison 1975). From the measurements, graphs have been constructed showing the rates of fall of exponential mean air and soil temperatures with rising altitude in the range 275–686 m O.D. (Jones and Court 1980). Lapse rates of 0·64 °C per 100 m for air and 0·61 °C per 100 m for soil temperatures are reported and these are similar to those measured or estimated over wider altitude ranges by Gloyne (1971), Manley (1945, 1952) and Oliver (1964).

(4) *The effect of aspect on temperature.* It has not been possible to assess the effect of aspect on mean temperatures measured at the 14 meteorological stations (Figure 1). However, using sucrose inversion measurements from the herbage sites, Jones and Tinsley (1980) found that southern aspects between 330–550 m O.D. were warmer during early summer when growth rates increase rapidly.

From the bi-monthly exponential mean temperatures shown in Figure 6 it is clear that the effect of aspect on $\theta_{e(a)}$ and $\theta_{e(s)}$ values is confined to April, May and June. During July, August and September the effect was not significant, presumably because most of the sites were on gentle or moderate slopes (3–7 degrees) which reduced the advantage of southern aspects. For grass growth, it is important to note that the average $\theta_{e(a)}$ value during May and June was below 12 °C ($\theta_a \approx 10$ °C, a threshold for vigorous growth) on north aspect sites but above that figure on south-facing ones.

These findings accord with the observations of Garnett (1939) that, in high latitudes, south facing slopes are not always the most favoured in every respect. She concluded from her experiments at Kinlochleven that the law of 'adret and ubac',* which applies so widely in Alpine regions of lower latitude, does not determine agricultural activity in deep Highland glens. In the Upper Don Basin

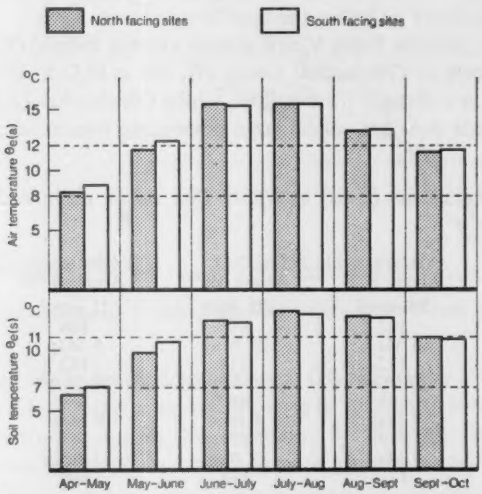


Figure 6. Effect of aspect on bimonthly mean exponential air ($\theta_{e(a)}$) and soil ($\theta_{e(s)}$) temperatures for pasture sites 330–550 m O.D. in 1969.

* These words come from the dialect of south-east France: *adret* means the sunny side of an Alpine valley or mountain and *ubac* the shady side.

and other areas of northern Britain where the slopes do not exceed 15 degrees and the ranges of altitude are small, the differential effect of aspect on light intensity and day length is minimal.

(5) *Growing season.* Peacock (1975, 1976a) studied the effects of air and soil temperatures on the growth of *Lolium perenne* at the Grassland Research Institute, Hurley (51° 31′N, 0° 48′W, altitude 50 m O.D.). Leaf extension was very slight when the air temperature around the shoot apex was 2–6 °C: such mean temperatures in the crop were closely correlated with air temperatures at standard screen height of 1·25 m. This species responded exponentially to temperature rises over the range 2–10 °C. In further studies involving subsurface increases of soil temperature, Peacock (1976b) followed the growth of four grass species into the flowering stage at temperatures up to 20 °C and reported an overall linear response to temperature for timothy and perennial and Italian ryegrasses but an exponential trend for tall fescue. However, if the data for the raised soil temperature treatments are excluded the leaf extension responses for all four species were broadly curvilinear in the range 2–16 °C.

Hence these studies lend support to the view of Gloyne (1958) that the conventional practice of defining the length of growing season as the period of the year when the mean air temperature at the standard height exceeds 42 °F (5·6 °C) is useful for evaluating the impact of climate on agricultural production, especially in the hill areas of Britain.

The notion of two threshold steps is introduced here, namely (i) the standard growing season above 6 °C (GL) and (ii) a 'high' growing season above 10 °C (HGL) in the light of the observations by Grant (1968) and Alberda (1966) that growth of sward species becomes vigorous only as the mean temperature rises to 10 °C and above: growth declines at temperatures above 28–30 °C.

From the graphs of 5 day mean θ_a and θ_d values for Stations I and II, (i) the standard growing season above 6 °C (GL) and (ii) a high growing season above 10 °C (HGL) have been estimated. In both cases the season was considered to have begun and ended when the temperature for two consecutive 5 day periods was above or below the base temperature.

Growing season data are listed in Table V and give an average length, GL, of 171 days at Waterside (I, 275 m O.D.) and 188 days at Glenbuchat Lodge (II, 381 m O.D.). Waterside is a valley bottom site close to the river Don in a distinct frost hollow, whilst Glenbuchat Lodge is at the head of a glen and though higher in altitude does not collect large descending masses of cold air. The high growing

Table V. *Length of growing season (days) in Upper Don Basin, estimated from plots of 5 day mean values of* θ_a *and* θ_d

		I Waterside 275 m O.D.		II Glenbuchat Lodge 381 m O.D.	
		Above 6 °C	Above 10 °C	Above 6 °C	Above 10 °C
1966	S	24 April	28 May	21 April	26 May
	L	162	98[1]	166	128
1967	S	6 May	29 May	5 May	26 May
	L	172	113	162	128
1968	S	20 May[2]	26 May	21 May[4]	27 May
	L	163	101[3]	161	105[5]
1969	S	7 May	4 June	9 May	2 June
	L	179	101	177	103
1966–69	S	9 May	29 May	23 April	27 May
	L	171	118	188	118

S is start, L is length

Notes:
1. The temperature was below 10 °C for almost 3 weeks in August.
2. The temperature rose above 6 °C between 15 April and 2 May.
3. The temperature was below 10 °C for 10 days in July.
4. The temperature rose above 6 °C between 12 April and 2 May.
5. The temperature was below 10 °C for 7 days in July.

season, HGL, when from the farmer's point of view herbage can be expected to grow vigorously, was estimated as 118 days at both sites.

The effect of altitude on growing season has been discussed by Manley (1945, 1952). Of considerable importance is a shortening of the period and reduction in the amplitude of the annual curve of average temperature with increasing height above sea level. In similar investigations, Gloyne (1958) showed that the length of the growing season (GL) at any place will change relatively uniformly with height above mean sea level, provided $\theta = 6$ °C does not cut the curve near its highest or lowest point. Further the amplitude of the curve will affect the reduction of GL with increasing altitude and, the more continental the climate, the less the effect will be.

In the absence of sufficient temperature data from standard instruments, mean monthly $\theta_{e(a)}$ values for five stations (350–700 m O.D.) for 1966–69 have been used to construct the temperature curves in Figure 7 for deducing the effect of altitude on growing season. Mean $\theta_{e(a)}$ values of 8 °C and 12 C° were chosen to correspond with 6 °C and 10 °C measured by standard methods (θ_a) for calculating GL and HGL.

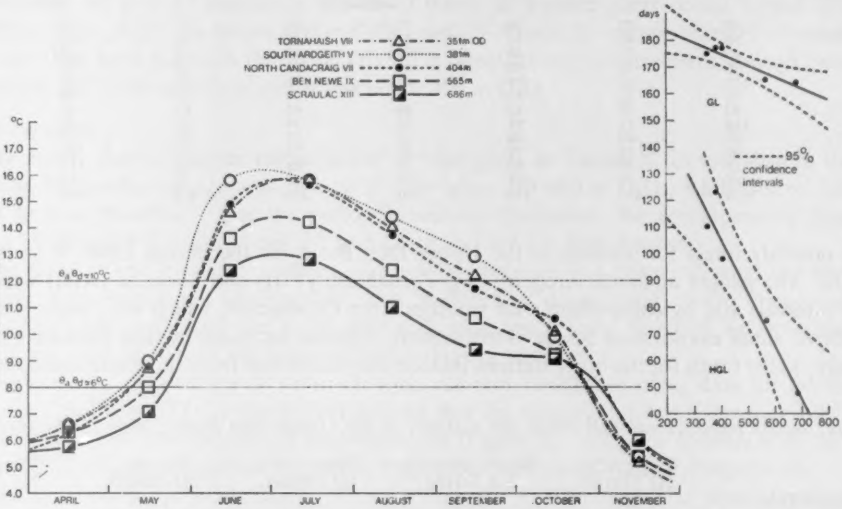


Figure 7. Effects of altitude on length of growing season in the Upper Don Basin, 1966–69.

The relationship with altitude is clearly demonstrated; GL reduces by about 10 days for every 200 m rise in altitude, though the relationship is imprecise owing to poor distribution of points; HGL reduced by 10 days for every 50 m rise in altitude, the regression being highly significant. Between 350 and 700 m O.D., in Upper Donside, the change in HGL with altitude is much more significant than the corresponding change in GL.

Tornahaish (VIII) had virtually the same GL but a significantly shorter HGL value than South Ardgeith (V) despite the fact that the former is 30 m lower in altitude than the latter. These results demonstrate the local influence of topography since Tornahaish is situated in a frost hollow whereas South Ardgeith is on a gentle slope with a southern aspect. By contrast North Candacraig (VII), Ben Newe (IX) and Scraulac (XIII) are hilltop (summit) stations.

The period above 10 °C is probably more important than that above 6 °C for the growth of cool temperate crops, suggesting that these results have added significance in assessing the potential productivity of grassland in the uplands of the Grampian Region.

(c) *Precipitation*

Rainfall data from stations in north-east Scotland are given in Table VI, for the period 1964–70. Totals for Glenbuchat Lodge (II) at 381 m O.D. are the highest, Derry Lodge and Corndavon Lodge both at 427 m O.D. recording smaller mean annual totals. The normal total of about 1000 mm for the region is evenly distributed through the year with roughly half falling between the beginning of May and the end of October.

Table VI. *Mean monthly rainfall in Glenbuchat in relation to other stations in north-east Scotland, 1964–70*

Station	Glenbuchat	Braemar	Glenlivet	Dinnet	Craibstone	Balmoral	Derry Lodge	Corndavon Lodge
NGR	NJ 333188	NO 152914	NJ 188303	NJ 446025	NJ 872107	NO 260947	NO 036932	NJ 228021
Altitude (m O.D.)	381	339	215	177	91	283	427	427
				millimetres				
Jan.	40	71	56	72	86	77	77	74
Feb.	58	62	55	51	63	70	81	66
Mar.	85	56	60	49	47	63	67	62
Apr.	78	58	62	59	53	67	63	74
May	111	83	79	81	92	85	88	95
June	66	63	63	52	59	57	79	60
July	92	55	63	68	66	63	67	75
Aug.	114	71	99	76	79	78	87	98
Sept.	87	80	80	65	63	66	85	80
Oct.	99	84	79	62	74	74	109	94
Nov.	121	80	96	66	68	85	113	92
Dec.	87	70	81	60	66	77	85	89
Totals	1038	833	873	761	816	862	1001	959

Mean monthly totals for stations in the Upper Don Basin for the period 1966–70 are shown in Table VII. The gauges at South Ardgeith (V), Tornahaish (VIII) and Scraulac (XIII) were read at monthly intervals and by comparison with readings from Glenbuchat, which were made daily, could have suffered small evaporation losses. Furthermore, Glenbuchat totals include snowmelt, also measured daily, whilst totals for the other stations include only meltwater from snow retained in the funnel.

Table VII. *Mean monthly rainfall totals for stations in the Upper Don Basin, May 1966–April 1970*

Station	Glenbuchat	South Ardgeith	Tornahaish	Scraulac	Edinglassie*
NGR	NJ 333188	NJ 397102	NJ 296084	NJ 309055	NJ 328123
Altitude (m O.D.)	381	381	351	686	358
			millimetres		
May	147	113	112	106	117
June	70	65	66	77	40
July	69	59	52	43	82
Aug.	78	73	76	74	95
Sept.	63	56	53	76	63
Oct.	118	96	100	84	93
May–Oct.	545	462	459	460	490
Nov.	117	72	90	132	76
Dec.	87	75	84	69	91
Jan.	43	118	119	92	116
Feb.	(58)	55	76	112	74
Mar.	(85)	44	79	70	73
Apr.	82	63	85	80	102
May–Apr.	1017	889	992	1015	1022

Figures in brackets are estimates for the period 1964–70.
* 1967–70.

On mountain tops, such as Scraulac, snow accumulations on the gauge could periodically have been blown away. Nevertheless, the records show that the Upper Don Basin is moderately dry for its height above sea level and the rainfall pattern is not markedly affected by altitude.

Snowfall begins as early as October or November and on high ground snow cover persists into May or early June, particularly on north-facing slopes above 800 m O.D., where thick drifts often build up during the winter. Records kept at Candacraig House (305 m O.D.) for 1961–67 show that on average snow falls on 45 days in any one year, the range being from 26 to 61 (Jones 1971). A similar pattern was found at Achnagoichan (305 m O.D.) in the western Cairngorms by Pears (1965).

(1) *Soil moisture deficit*. Average potential transpiration estimates for west Aberdeenshire were interpolated from Smith (1967) and compared with monthly rainfall totals for 1964–70, as described by Jones and Evans (1975) and Jones (1979). These permit the calculation of the potential soil moisture deficit (PSMD), the cumulative total excess transpiration over rainfall, and it was found that Station II suffered a significant (>40 mm) accumulated PSMD in only two years (Table VIII). In 1967 and 1969 the accumulated PSMD reached 65 mm and 42 mm respectively at the end of July. Birse and Dry (1970) calculate an average maximum PSMD of 0 mm in western parts of the Upper Don Basin above 400 m O.D., 0–25 mm below 400 m O.D., and 25–50 mm in eastern parts of the basin below this altitude. For most purposes therefore, rainfall is adequate but not excessive, though occasionally a small deficit will occur in soils at elevations below 400 m O.D.

(d) *Wind exposure*

(1) *Flag tatter*. Average tatter values in $cm^2 d^{-1}$ are given in Table IX for five sites in the Upper Don Basin; the yearly average was 2–4 $cm^2 d^{-1}$ for sites 270–400 m O.D., whilst above 500 m this increased to over 20 $cm^2 d^{-1}$. For the period November–December, the corresponding figures were 2·5–6 and 25–30 $cm^2 d^{-1}$, and 1–2 $cm^2 d^{-1}$ and 12–18 $cm^2 d^{-1}$ for July–August.

Ignoring tatter values for damaged flags, relationships between flag tatter and wind run by cup-type anemometer were examined. Dealing first with 'within site' dependency, strong linear correlations were found between untransformed tatter data and wind run (Figure 8) which agrees with Rutter's (1966) findings from studies of the tattering of dry flags in wind-tunnels.

The 'between site' dependency of tatter on wind run was established using data for the three sites in the range 270–570 m O.D. Jones (1971) showed that the square-root transformation of flag-tatter data against wind run gave the best fit regression line (Figure 8). This also accords with the findings of Rutter (1968) who experimented with tatter flags under field conditions at Aberystwyth.

Different expressions were calculated for the 'within site' and 'between site' dependencies of tatter on run of wind or mean wind speed. Tatter at individual sites is linearly related ($F = a + bW$) to run of wind, except when ribbon tearing causes excessive losses, whilst tatter between sites, ranging from very sheltered to very exposed, is curvilinearly related to run of wind (Rutter 1968; Jones 1971): $\sqrt{F} = a + bW$ where F is area loss (in $cm^2 d^{-1}$), W is wind run or mean speed ($km d^{-1}$), and a, b are constants.

Although tatter flags have not previously been used as a direct substitute for anemometers, the correlation is sufficiently close to suggest that they may be so employed. However, if flags are to be used for direct intersite comparisons, it must be recognized that exposure to wind can be exaggerated by rain, even within a small range of exposure (Rutter 1966) and a limited number of anemometers will still be desirable.

Correlations of geomorphic shelter with flag tatter were studied; those of shelter index against average annual and May–October area loss by flag tatter were strongest, though a maximum of only 28 per cent of the variation was accounted for. Geomorphic shelter can therefore be regarded as a

Table VIII. *Accumulated potential soil moisture deficit for Station II (381 metres O.D.)*

		1964				1965				1966				1967				1968				1969				1970			
Month	PT	R	PSMS	PSMD	APSMD	R	PSMS	PSMD	APSMD	R	PSMS	PSMD	APSMD	R	PSMS	PSMD	APSMD	R	PSMS	PSMD	APSMD	R	PSMS	PSMD	APSMD	R	PSMS	PSMD	APSMD
														millimetres															
Jan.	−3					27	30			45	48			35	38			84	87			10	13			42	45		
Feb.	4					79	75			89	85			84	80			54	50			—	—			6	2		
Mar.	17					50	33			125	108			105	88			59	42			—	—			—			
Apr.	41					129	88			27		13	13	95	54			160	119			58	17			17		24	24
May	64	34		30	30	100	36			123	59			129	65			184	120			151	87						
June	71	72	1		29	63		8	8	162	91			35		36	36	37		34	34	48		23	23				
July	67	77	10		19	113	46			84	17			36		31	65	108	41			48		19	42				
Aug.	48	196	148			88	40			107	59			80	32		33	43		5	5	81	33		9				
Sept.	29	107	78			188	159			54	25			92	63			73	44			34	5		4				
Oct.	11	52	41			59	48			154	143			137	126			109	98			74	63						
Nov.	0	59	59			154	54			256	256			92	92			71	71			50	50						
Dec.	−4	50	54			138	142			169	173			138	142			11	15			30	34						

All data in millimetres.

PT — Average potential transpiration figures from Smith (1967) for Aberdeenshire (high level areas—365 m O.D.)
R — Actual rainfall totals
PSMS — Potential soil moisture surplus or the excess of rainfall over average PT
PSMD — Potential soil moisture deficit or the excess of average PT over rainfall
APSMD — Accumulated (month by month) PSMD

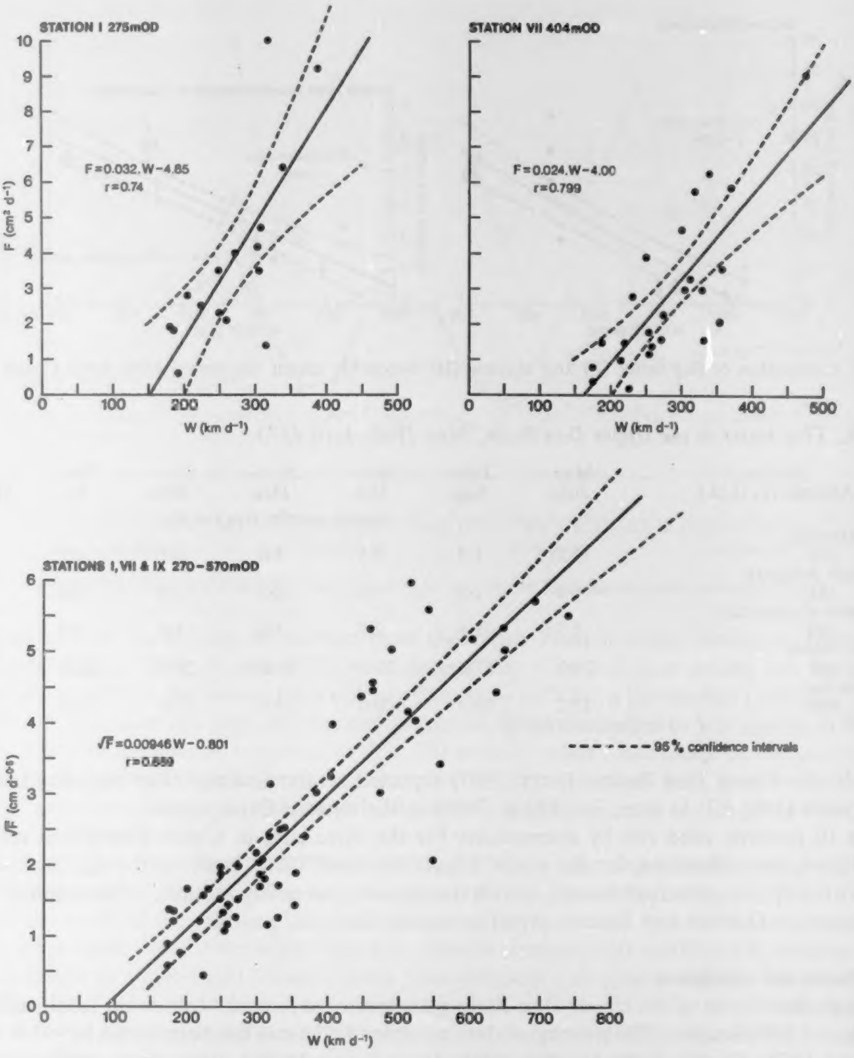


Figure 8. Relationship between flag tatter (F) and wind run (W).

diagnostic index which allows only crude ranking of sites according to relative exposures and it is understandably not closely related to average wind speed.

(2) ***The effect of altitude on exposure.*** **Average annual flag tatter, calculated from bi-monthly values, correlated strongly with altitude (Figure 9). The best fit was obtained with square-root transformation of the tatter data. The tatter-flag method therefore clearly reveals a marked increase in exposure with**

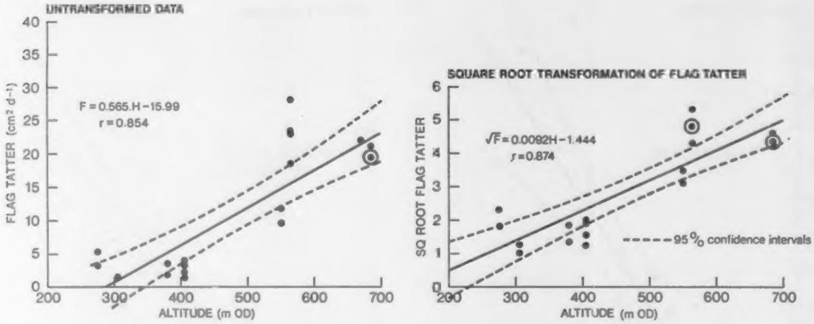


Figure 9. Correlation of flag tatter (F) and altitude (H) bimonthly means for period May–April (Year) 1966–70.

Table IX. *Flag tatter in the Upper Don Basin, May 1966–April 1970*

	Station Altitude (m O.D.)	May–June	July–Aug.	Sept.–Oct.	Nov.–Dec.	Jan.–Feb.	Mar.–Apr.	Year May–Apr.
				square centimetres per day				
I	Waterside 275	(3·2)	1·2	2·3	5·6	4·7	4·7	3·6
V	South Ardgeith 381	1·5	1·2	1·8	2·5	2·4	2·9	2·0
VII	North Candacraig 404	1·3	1·1	2·7	3·6	4·5	4·0	2·9
IX	Ben Newe 565	24·2	17·6	27·3	30·8	22·1	22·4	24·1
XIII	Scraulac 686	17·2	12·2	20·0	25·6	27·8	19·8	20·4

( ) some data missing.

altitude in the Upper Don Basin. Pears (1967) reported similar findings after exposing tatter flags for two years (1961–63) at sites (381–884 m O.D.) in the western Cairngorms.

Figure 10 presents wind run by anemometer for the three sites in Upper Donside in relation to Dyce Airport, near Aberdeen, for the period May 1966–April 1970. It shows the significant increase in mean wind speed, measured directly, which occurs with increasing altitude. The windiest periods were September–October and January–April during the four year period.

4. Discussion and conclusion

Although the climate of the Upper Don Basin was monitored for only 4 years the results add to our knowledge of hill climates. The paucity of data on upland climates has been noted by other workers (Crompton 1958; Gloyne 1968; Harding 1978; Hughes and Munro 1968; Jones 1967; and Oliver 1964) and, although attempts have been made to rectify the problem, it is still necessary to draw on the long-standing observations of Buchan (1905) and Manley (1936, 1942) for insight into extreme conditions. Particularly relevant here, however, are the results published by Munro (1973) describing the climate of hill centres (30–335 m O.D.) in Wales for the same period (1966–69) as the Donside records, and the review of upland temperature data by Harding (1978).

(a) *Solar radiation*

Although lower in June, solar radiation continued to be higher in the Upper Don Basin (350–670 m O.D.) than at Aberdeen (30 m O.D.) on the coast throughout August and September 1969. These

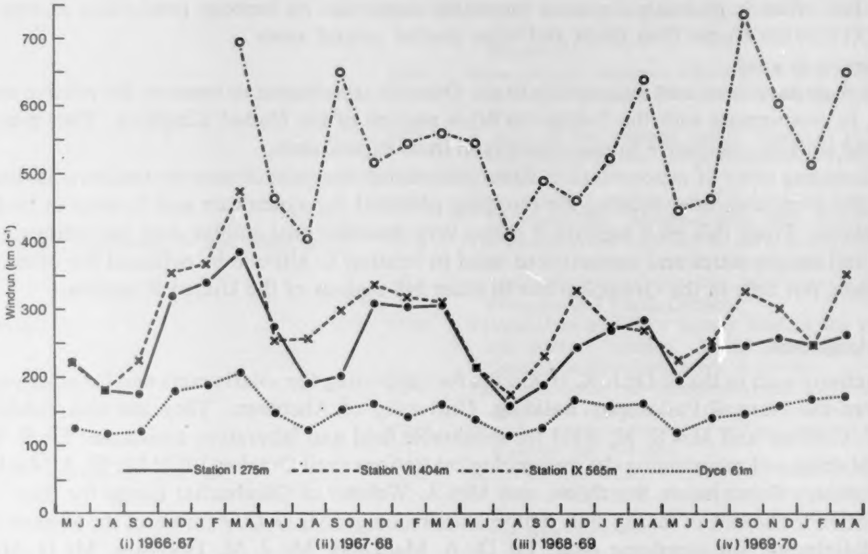


Figure 10. Anemometer wind run (km d^{-1}) in the Upper Don Basin compared with Dyce.

results concur with the findings of workers from the Welsh Plant Breeding Station in North Wales (Hughes and Munro 1968; Munro 1973) who showed that solar radiation during late summer was higher at 305 m O.D. in the drier eastern uplands than at 30 m O.D. in the western lowlands. Furthermore, the fact that from late July until the end of August 1969 solar radiation was greater at the Lecht site (XII, 670 m O.D.) than at Tornahaish (VIII, 351 m O.D.) casts some doubt on the generally held view that insolation declines with increasing altitude. The data presented here, however, are far from exhaustive and more work is needed to establish whether they represent a consistent pattern.

(b) *Air and soil temperatures*

The successful use of a cheap and effective method of mean temperature measurement (by sucrose inversion) at numerous diverse sites is a significant advance in agricultural research. The method has permitted the study of the variation of mean air and soil temperatures with altitude and aspect on a relatively large scale. Whilst the lapse rates with altitude compare with traditionally accepted values, there is evidence to suggest that measurements from standard instruments did not adequately reflect the significance of declining temperatures on plant growth over the relatively small altitude range of 270–670 m O.D. As Jones and Court (1980) point out, the exponential mean is probably more useful for demonstrating temperature differences between sites of different topography than the mean from standard instruments.

(c) *Growing season*

Standard measures of mean daily air temperature have been used to estimate the growing season above 6 °C and a 'high growing season' above 10 °C. These data permit comparisons with other parts of Britain. However, by using the relationship with arithmetic mean air temperature, exponential means for 1966–69 measured at several sites have revealed the effect of altitude on growing season with greater sensitivity. The period above 6 °C declines significantly with altitude in the range 350–700 m O.D. but more significantly there is a 50 per cent reduction in the period above 10 °C within this

range. This effect is probably the most important constraint on herbage production at sites above 350 m O.D. in the Upper Don Basin and other similar upland areas.

(d) *Exposure to wind*

Tatter flags have been used successfully in the Donside experiments to measure the relative exposure of sites, in concurrence with the findings in other regions of the United Kingdom. They provided a cheap and suitable alternative to anemometers in these experiments.

The foregoing array of meteorological data characterizes the mesoclimate in considerable detail and should prove valuable in evaluating the cropping potential for agriculture and forestry in land capability studies. From this pilot exercise it seems very desirable that similar data on summer rainfall, air and soil temperatures and exposures to wind in relation to altitude be collected for other upland catchments, not only in the Grampian but in other hill regions of the United Kingdom.

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Archiving and quality control of climatological data

By G. W. Bryant

(Meteorological Office, Bracknell)

Summary

A very large amount of climatological data is now handled every month by the Climatological Services Branch. As a result, a routine procedure has been developed which uses computer methods to control the quality of and to archive the data. An account of this procedure is presented together with a brief description of some of the quality control techniques which are used.

1. Introduction

Meteorological observations for climatological purposes have been made at stations throughout the United Kingdom for many years. The data are transcribed at the stations on to manuscript forms which are returned monthly to the Meteorological Office where they are held as permanent archive records; since 1884, the data have been published in the *Monthly Weather Report*. Some 30 years ago, the need for more powerful methods of climatological data processing led to the use of punched cards, which had already been used successfully with marine data. More recently, climatological archives have been compiled on magnetic tape, and the availability of information in this form has made possible much greater and more sophisticated exploitation of the data for research and enquiry purposes. Moreover, computer processing methods have a further major advantage in that a much more consistent and rigorous inspection of the data can now be undertaken.

During the transfer from visual and instrumental observations to archive records the information is first recorded in the observation register and is then transcribed to manuscript tabulations at the station; on receipt at the Meteorological Office, data are keyed to disc and are subsequently transferred to magnetic tape. With about 650 stations in the United Kingdom now making returns, over 3 million pieces of information go through this process every month, and errors can occur at every stage. Detailed quality control of this volume of data by visual inspection is quite impracticable, but by the use of computer methods all the data are subjected to a large number of quality control checks; corrections are made at several stages in the course of data entry, and archived data are now of very high quality.

The introduction of computerized methods of quality control required the solution of many problems. Although the solutions must depend both on the type of data and on the computing power available, the problems themselves must be common to all national meteorological services faced with the need to archive climatological data. However, apart from the general survey of Filippov (1968) and descriptions of the methods used in Canada (Potter 1969) and Israel (Walther and Elbashon 1974), there appears to be little published information on the subject. The following report describes the techniques which have been developed during the past few years by the Meteorological Office, and which are currently used for land surface data by the Climatological Services Branch.

2. Types of data

The stations recording climatological data within the United Kingdom vary greatly in the facilities that they have available and the hours during which they can operate and this is reflected in the type and volume of data submitted to the Meteorological Office.

The largest volume of data is collected by official Meteorological Office stations which are staffed by trained observers who make a full range of observations, usually every hour. Data recorded include

not only such fairly standard items as wet- and dry-bulb temperatures, pressure, visibility and present weather but also more detailed observations such as hourly rainfall amounts and duration, hourly mean wind speeds and directions (usually), and the type, height and amount of low, medium and high cloud. There is some variation but each station observes about 30 weather elements each hour of the day, and is referred to as an 'hourly station'. There are about 50 such stations in the United Kingdom; their main purpose is to offer forecasting services to the public, to commercial interests and to military and civil aviation. Most of them are in fact based at airfields and weather centres.

Many Meteorological Office stations which would otherwise be included in the list of hourly stations are not staffed to make hourly observations throughout the day. Auxiliary stations, whose prime duties do not involve forecasting, are in a similar situation and these all form a class of 'fixed hourly stations' which, wherever possible, make observations at each of the eight synoptic hours (00 GMT, 03 GMT, 06 GMT and so on). However, some stations do not operate at night, others close at weekends, and at some (coastguard stations, for example) the observer may be called away on more pressing duties. The result is a considerable variation of frequency of observation among these stations.

Both the hourly and fixed hourly stations also complete a monthly summary of daily values. This summary includes day and night maximum and minimum temperatures, grass and concrete minimum temperatures, rainfall totals, sunshine duration, 09 GMT soil and earth temperatures and brief weather descriptions which indicate the occurrence during each day of events such as fog, hail and snow.

The official stations are, however, in the minority; the majority of stations are operated by voluntary observers. These are known as 'co-operating stations', and are maintained by such diverse groups as health resorts, schools, water authorities and many private individuals as a voluntary service. Most of these stations supply their own instruments which are inspected regularly by Meteorological Office staff. Observations are made only once per day at 09 GMT and the range of data reported is restricted in some cases by the availability of suitable instruments. The items reported by co-operating stations are generally similar to those in the summary of daily data mentioned above with the addition of such items as spot wind speed and direction, visibility and pressure which relate only to conditions at the observing hour, usually 09 GMT. Although the standard of data tends to be rather more variable than at the hourly and fixed hourly stations, the co-operating stations form an extremely valuable part of the climatological network in the United Kingdom.

Finally, there is an anemograph network of about 160 stations; these are each equipped with an anemometer usually exposed at a height of about 10 m above the ground. They tabulate, from the anemograph traces, the speed and direction of both the hourly mean wind and maximum gust in each hour. Some of these stations are also part of the climatological network and a few are equipped with a second anemometer at a higher level.

3. Data archiving and quality control

At the end of each month, the observations are transferred to the appropriate forms which are then sent to the Meteorological Office. The forms arrive at a fairly steady rate for the first three weeks of the following month, by the end of which time about 80 per cent of them have been received. Thereafter, the forms arrive at a slower rate and it is usually another three weeks before the last of them are available. Because of these late arrivals, there is always some overlap from month to month but the aim is to complete the processing of each month's data before work begins on the next. For this reason, the archiving and quality control system has been formed into a standard sequence which, although it is a continuous process, may be regarded as consisting of four distinct stages which will now be described in detail.

(a) *Data entry*

The process begins during the second week of each month when the forms are examined by scrutineers to ensure that the items known as indicatives (month, year and station number) have been correctly entered. This is vital because, throughout the rest of the process, these items are the only means by which the computer can identify the data and assign them to the correct data-sets. When the indicatives have been checked and, if necessary, corrected, the forms are passed to the keying section.

The keying section at the Meteorological Office is equipped with a Seecheck data entry system. This consists of a minicomputer controlling 19 keying stations each with a keyboard, similar to that used in a typewriter, and a screen which displays the line of data being keyed. Each keying station, acting independently of the others, is used to key data directly to magnetic disc storage.

The data are keyed at a rate of 12 000 key depressions per hour and even with the simplification that the data are mostly numerical, keying errors are inevitable. These only occur at a rate of about 2 errors per 1000 key depressions but since a single error can corrupt a complete observation, they can present serious problems. Quality control at this stage has, therefore, become very important. Some elementary checks are carried out during keying. For example, the hour or day is keyed at the beginning of each line and a count reveals any missing or duplicated observations. The main check, however, consists of complete re-keying of the data in verification mode by a different operator. If there is a discrepancy between the results of the first and second keyings, the keyboard being used for verification will lock until the query is resolved.

The minicomputer is capable of limited quality control operations and possible applications are being investigated. However, at present, verification keying offers the most reliable method of ensuring that the data are accurately transcribed from the manuscript to the computer data-sets.

After verification, the data are sorted from the keyed order to files based on the type of data (hourly or daily, for example). Once this has been completed, the data are transferred to the main computer for archiving and quality control.

(b) *Data archiving*

At this stage, the files contain only the data which happen to have been keyed during that particular day and these data are now added to more permanent (archive) data-sets. With the exception of hourly data (which includes fixed hourly data), archive data-sets are prepared at yearly intervals for each type of data (daily, anemograph, soil and earth temperatures, and observations made at 09 GMT). Each of these sets has space for data for all stations for an entire year and they are retained on line until complete. Because of their much greater volume, hourly data are stored in monthly data sets.

The archive data-sets have been carefully designed to achieve compact storage and easy access and to facilitate the subsequent copying of data to single-station archive sets. A series of accessing subroutines has been written in the Meteorological Office specifically for use with this type of data-set but the design also offers considerable advantages with standard access methods.

The data are stored as half-word binary integers which, for the IBM system, have a range of −32 768 to +32 767, sufficient for all surface climatological values. Each data-set has the same basic design of a main header block followed by a series of data blocks each beginning with a short, descriptive, header record. For yearly data-sets, each block contains data for one station-month and the blocks are stored by month so that all the data for a given month follow those of the previous month. Within the monthly groups, the data for each station always occupy the same relative position. The main header block contains an index which gives the first block number for each month and the relative block number of each station within each monthly group. The data for each station-month are thus easily located.

The format of the hourly data is very similar except that each block contains data for one to eight days, depending on the number of observations made each day. In this case, all the data for each station are stored together.

Each completed set is transferred to magnetic tape soon after the new one is created, with some overlap to allow for the late arrival of data.

(c) *Internal quality control*

The transfer of data to the main data-sets is completed before quality control begins. There is, however, a preliminary format check carried out during the transfer which examines each line of data for errors such as illegal characters, invalid overpunches, embedded blanks or characters in the wrong field. The data should be mostly numerical, so this type of error suggests serious corruption of that line of data and the entire line is printed out for inspection and re-keying.

Errors in format are relatively rare and so the main quality control process is part of the same program and begins after transfer of the data but before any corrections are made. The first step in the main process, carried out only for 09 GMT and daily data, consists of a check for missing data and the computation of totals and means and statistics such as the number of days with rainfall or air frost. Subsequently these statistics can be compared with the values entered on the original form.

The next step, which varies with the type of data, involves a large series of tests. The first and simplest of these requires that the values of the various elements should fall within a valid range. For most elements, the ranges are constant but for temperature and sunshine they are made to vary with the month; the possibility of making them a function of latitude is being investigated. The second type of check involves an examination of internal consistency of observations, and this is rather more complex in that it ensures that the parameters observed at a particular hour are consistent with each other. For example, dry-bulb temperature should not be less than wet-bulb temperature and the amount, type and height of low, medium and high cloud should all be mutually consistent. A wide range of checks can be applied to the data using the past and present weather codes in the hourly and fixed hourly observations.

This step concludes with time sequence checks which are mainly used with hourly and fixed hourly data and ensure that each value of temperature, pressure, wind speed and wind direction is consistent with the preceding and subsequent values. This test is of limited use because it assumes that the element concerned should change by only a relatively small amount between successive measurements. Consequently, its use with daily data is confined to soil and earth temperatures.

This program generates queries at a rate of about 10 000 per month and these are passed back to the quality control scrutineers, each of whom has responsibility for checking the data for a particular area containing up to 100 stations. Checking begins with a comparison between the queried values and those entered by the observer on the manuscript form; this eliminates keying errors missed by verification. If the keyed value agrees with that on the form then the data must be examined more closely. The interrelationship between various elements often makes it fairly easy to judge the validity of a query and to calculate the correct values. (A typical example would be cloud type reported as cirrus but cloud height coded as 020 (2000 ft) instead of 200 (20 000 ft)). Each of the scrutineers specializes in a particular group of stations and this allows them to become acquainted with local effects. In doubtful cases, the observer is contacted to compare the queried value with that in the observing station's register; in such a situation, the observer's decision is usually accepted.

The computer print-out lists with each query an immediately keyable error message consisting of the indicatives including date and (if applicable) hour, a mnemonic for the type of element being queried and a code giving the reason for the query. With the addition of the correct value, this message then

contains all the information necessary for the corrections to be made, and the further addition of a standard marker causes an entry to a quality control data-set. A batch of such messages can then pass through the keying section to the computer in much the same way as the original climatological data.

About 50 per cent of the queries raised by the computer quality control are rejected at this stage as spurious, and require no further action. Of the remainder, about 40 per cent of the queries are accepted and are due to keying or transcription errors. The remaining 10 per cent fall into a different category where, although there is a firm belief in the validity of the new value, there remains a slight possibility that the original value may have been correct. It is a World Meteorological Organization requirement, in this situation, that both the old value and the reason for the change should be preserved. The quality control data-set, referred to earlier, was therefore created to hold this information.

When the corrections have been made, the only step remaining in this intermediate stage is to re-run the quality control checks to ensure that the corrected values and the rest of the data are mutually consistent. Throughout the month, therefore, all incoming data are processed in this way to build up data-sets which are relatively error-free.

(d) *Quality control by spatial comparisons*

The data may be regarded as substantially correct as soon as the queries raised by internal quality control have been dealt with. However, there are a number of elements whose values are not easily checked by any of the preceding programs and so a series of spatial checks has been introduced. These are based on the principle that climatological parameters measured at neighbouring stations are likely to be correlated to some extent. Such parameters can therefore be checked by comparison after allowance is made for differences in station altitude or topography.

Ideally, such comparisons should be made within groups of about ten stations but the dense network which this requires is only available for daily data. Areal quality control, as opposed to interstation comparison, is therefore only used to quality control maximum and minimum temperatures and sunshine duration. For this purpose the UK, excluding Scotland, is divided into areas containing between seven and fourteen stations which are regarded as having a similar climatology. Quality control then begins by 'normalizing' the daily values for each station. For temperature, this is done by subtracting the station value from the monthly mean temperatures while sunshine values are normalized by dividing the station value by the monthly mean sunshine duration. Each normalized value is then compared with the mean of the values from all the other stations in that area for that day. The value is queried if it differs from this mean by more than two standard deviations and either 2·5 °C for temperature or 20 per cent for sunshine duration. When a value is queried, it is excluded from further analysis.

Areal comparison was found to be unsatisfactory for Scotland where the complex topography greatly reduced the number of stations in each area, and so the second program in this series was developed. For the Scottish stations, the values of the temperature extremes for each station are compared with those at two neighbouring stations and queried if they differ from both by more than 2 °C. However, quality control of sunshine duration proved impracticable except by inspection. This technique requires much more time from the scrutineers than those previously described and, to make the job easier, the print-out lists, for each Scottish station, the maximum, minimum, grass minimum and 09 GMT temperatures and the sunshine duration if reported. The print-out itself has been simplified by arranging the stations in a chain, with some breaks and duplications, in which each station is compared with the previous and subsequent stations.

The errors detected by these methods must obviously be fairly large to exceed the limits which have been set but half the queries are still rejected. The problem probably lies in the methods used to

select the stations which make up each area. More scientific methods involving factor analysis are being investigated and it appears that these will give more representative areas which will vary with element and weather type.

The two remaining programs both rely on interstation comparisons. The first of these checks pressure measurements at stations which do not report at all synoptic hours by comparing every such station with the nearest hourly station. The theoretical pressure difference between the two sites is first computed at all relevant hours by using the measured values of wind speed and direction to estimate the geostrophic wind field and, hence, the pressure gradient. From this value and the value of pressure at the hourly station, the pressure at the subject station is calculated. If it differs from the reported value by more than 1–2 mb (depending on the separation of the two stations) then a query is raised. Since the pressures reported at the hourly station will have been quality controlled by time sequence checks, the error is assumed to be in the data from the subject station.

The final program to be run is quite different from the others in that it checks for errors in the instrument rather than in transcription or keying. Every year, about 5 per cent of the anemographs in use in the United Kingdom network develop faults which are often only detected at the next site inspection. A quality control program has therefore been developed which can detect some of these faults by comparing the wind direction at each station with that at the nearest two stations.

There are usually differences between the hourly wind directions at any two sites in the short term owing to synoptic effects, and in the longer term owing to differences in topography and exposure. The program solves this problem by first estimating long term effects by examining past data and computing the average difference in wind direction at the two sites for each of the eighteen 20° sectors, using the wind direction at one of the sites as a reference. These eighteen values, which represent the steering effect of topography, are subsequently used to adjust the hourly wind direction at the second site to remove that effect. The differences in direction after adjustment are then averaged over the entire month to remove the short-term effects. If both anemographs are correctly adjusted and the exposure has not changed then the average difference should be close to zero and the standard deviation will be a measure of the short-term effects. When either value exceeds limits chosen for the two stations, a query is raised. If the scrutineer decides that the query is justified then the instrument is inspected and, if necessary, readjusted and any consequent corrections made to the data.

Conclusion

The large amount of climatological data reaching the Meteorological Office every month has led to the development of techniques which enable the data to be quality controlled and archived in machinable form on a routine basis. The quality control routines, which have involved considerable development work, ensure that very few significant errors in the data escape detection, while the archive methods are designed to achieve compact storage and easy access to the data.

The quality control and archiving of the data is not, of course, an end in itself. While the last corrections are being made, the data are already being processed for the preliminary run of the *Monthly Weather Report* which presents a published summary of the climatological data in the United Kingdom for the month. This publication, which was first produced in 1884, is still the most readily available source of climatological data and since 1974 has been largely produced by computer methods. However, the growing realization of the value of climatological data has led to a considerable increase in requests for more detailed information from industry, farming and research organizations. This has been enhanced by the ability to produce complex analyses with the aid of the computer. There is also a

large demand for data by such bodies as the Ministry of Agriculture, Fisheries and Food, the Department of Energy, British Gas and the Central Electricity Generating Board, either for internal use or for dissemination to the public in processed form.

The effort which has been expanded has therefore helped to meet a commercial need for reliable land-surface climatological data in machinable format. Although there will continue to be gradual refinements of the procedures, this work is now virtually completed and similar attention is now being paid to upper-air and sea surface data where different problems occur.

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Major K. G. Groves, O.B.E., J.P., M.A., LL.M.

It is with great regret that we record the death on 7 March 1979 of Major K. G. Groves, co-founder with his wife of the L. G. Groves Memorial Prizes and Awards.*

Keith Grimble Groves was born on 31 December 1887, fifth of the nine children of James Grimble Groves, M.P., of Oldfield Hall, Cheshire, and educated at Uppingham and Trinity College, Cambridge, where he stroked the College boat to gain his oar and took the Law Tripos which saw him into the Middle Temple in 1912.

He joined the Territorial Army when it was first formed in 1908, and enlisted in the Inns of Court Regiment on 4 August 1914. He served in France, Salonika and Palestine and was mentioned in Haig's Despatches after Vimy Ridge.

He married Dorothy Atwater Moore, daughter of the American foreign editor of the *Daily Express* (and descendant of Ensign John Moore of the Civil War). Their only son, Louis Grimble Groves, was killed on 10 September 1945 when the Halifax in which he was Meteorological Air Observer hit a Cornish hilltop when returning from a sortie over the Bay of Biscay. The four Memorial Prizes were founded in his memory by his parents, and they had personally attended every presentation ceremony from 1946 at the Air Ministry (which after 1963 was incorporated in the Ministry of Defence) until prevented by illness last year.

Major Groves was awarded the O.B.E. in 1968 for 'services to the Royal Air Force'.

Although Keith Groves had enjoyed a varied and full life, both during the war years—and subsequently as Barrister, Chairman of Groves and Whitnall Ltd, and a most active Justice of the Peace in the Isle of Man—the Louis Grimble Groves Memorial Awards remained the mainspring in the lives of both his wife Dorothy and himself.

We offer to her our sympathy and respect.

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* A description of the awards is given in the *Meteorological Magazine* for February 1975 (Volume 104, p. 57).

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